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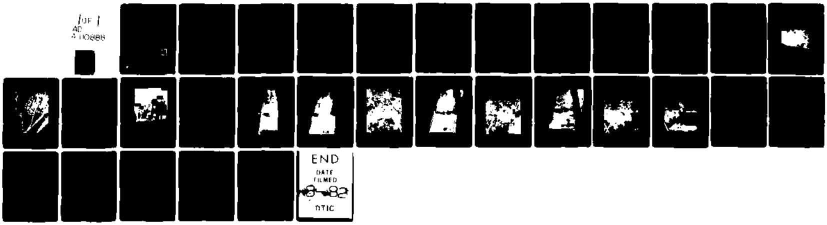

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A.J. Simmons

EHF Propagation Through Foliage

23 December 1981

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Lexington, Massachusetts

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FOR THE COMMANDER

Raymond L. Loiselle

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

EHF PROPAGATION THROUGH FOLIAGE

A.J. SIMMONS
Group 61

TECHNICAL REPORT 594

23 DECEMBER 1981

LEXINGTON MASSACHUSETTS

ABSTRACT

An EHF experiment was performed in which a 30-foot maple tree was placed between a 2-foot parabolic antenna and a distant transmitting site operating at 20 and 44 GHz. The objective was to measure attenuation through foliage. Results indicate that attenuation is nearly the same at the two frequencies. A value of 4 dB/meter can be used as a rough guide for deciduous trees in full leaf.

Measurements on single maple leaves and pine needle clusters plus a study of the literature tended to reinforce the conclusions of the tree experiment, and to show that evergreen trees can be expected to have similar attenuation values.

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I. INTRODUCTION

In connection with the development of a small transportable EHF satellite communications terminal (the SCOTT terminal) for USASATCOMA, we have examined the expected impact of parking the vehicle under a tree so that the line-of-sight between the terminal antenna and satellite is obscured by leaves and branches. The comments in this memorandum are based on a limited search of the literature, on Lincoln Laboratory measurements on individual leaves, and on a single Laboratory experiment in which a small maple tree was placed between a breadboard SCOTT antenna and a distant transmitting site.

Results of our investigation indicate that, in general, a value of 4 dB/meter for attenuation through foliage may be used as a rough guide in estimating system degradation. The implication of this is that (for the expected link parameters in the SCOTT system) voice communication would only be possible for light cover (1-2 meters) on a non-rainy day. For operational situations where thicker cover occurred (or was desired), communication might be possible at lower data rates. For example, our measurements indicate that TTY might be available under cover of up to 6 meters in thickness. For thicker cover than this, the terminal would have to be moved.

II. LITERATURE SURVEY

Most studies of propagation through foliage have been concerned with horizontal propagation, parallel to the ground, and have considered only much lower frequencies than EHF. Principal interest has been in the UHF band or lower frequencies, because of increased attenuation at the higher frequencies. Typical examples of such studies are References 1 and 2 which treat the frequency region below 1250 MHz. In this region, the leaves are small compared with wavelength. In Reference 1, the forest is treated as a homogeneous layer above the earth of some average conductivity, reducing the problem to one amenable to standard electromagnetic techniques. Such an approach is not useful at EHF where the leaves and the spaces between are large compared with wavelength, so that the assumption of homogeneity is not a good physical model. Reference 2 is concerned with the choice of the best frequency to use for tracking wild animals. In this case, scattering effects make the situation worse as frequency increases, compared with a homogeneous model for the vegetation.

Other studies are more concerned with radar clutter return from vegetation[3], and while they are of some general interest, they shed little quantitative light on the one-way communication loss.

A paper presented at the June 1980 URSI conference[4] summarized the current models for propagation through trees. A copy of the abstract of this paper is given in Appendix A. Briefly, the paper presents two formulas for attenuation, in dB per meter, through a grove of trees. The formulas are based on an empirical fit to data measured at frequencies below 10 GHz. The

two formulas differ drastically in their frequency-dependent term ($F^{0.77}$ vs $F^{0.284}$), and one of them requires a thickness dependence; that is, the attenuation per meter decreases as the distance through the foliage increases. (The hypothesis used to explain this peculiar effect is that some of the energy travels above the tree tops and is unaffected by the trees.) Extrapolating each of these formulas to 20 and 44 GHz, for the attenuation through 1 meter of foliage, yields the values in Table I.

TABLE I

ATTENUATION THROUGH ONE METER OF FOLIAGE, EXTRAPOLATION FROM LOWER FREQUENCY DATA

$\alpha =$	$0.26\ F^{0.77}$	$1.33\ F^{0.284}\ D^{-0.412}$
20 GHz	2.6 dB	3.1
44 GHz	4.8 dB	3.9

Because the two formulas are purely empirical, with no data above 10 GHz, extrapolation to the higher frequencies is questionable.

The most pertinent references are 5 and 6, in which measurements at various discrete frequencies up to 90 GHz are presented. These measurements were performed by radar techniques, using a corner reflector target embedded in the foliage and measuring two-way attenuation. The path was essentially horizontal, as contrasted to the high-angle path more likely with a satellite communications terminal. Another peculiarity of these data is that, in reporting the distance through the foliage, the researchers subtracted out the empty space between branches to get a more uniform set of data. This should tend to give higher values of attenuation per meter than others.

The experimental values presented at 16.2 and 35 GHz, the two frequencies closest to those of interest to the SCOTT terminal, are shown in Table II.

TABLE II

AVERAGE ONE-WAY ATTENUATION, GEORGIA TECH RESULTS

	Distance, meters		
Freq., GHz	1	2	3
16.2	2.2 dB	4.6 dB	7.4 dB
35	2.4 dB	6.3 dB	11.2 dB

These data seemed to show an increase in attenuation per meter with foliage thickness, rather than a decrease as postulated in Reference 4, particularly at the higher frequencies. The empirical formula suggested in References 5 and 6 to fit their data (which extended from 9.5 to 95 GHz) was $\alpha = 1.102 + 1.48 \log_{10}F$ dB/meter. This formula, applied to various frequencies, is presented in Table III. These numbers are somewhat higher than those in the first column of Table II, but compare closely with those in the second column of Table I. Agreement may be fortuitous, however, because the two studies used different approaches for defining foliage thickness. Nonetheless, based on these studies, it appears that an attenuation of about 3 dB/meter at 20 GHz and 3.5 - 4.0 dB/meter at 44 GHz can be expected.

TABLE III

ATTENUATION USING GEORGIA TECH EMPIRICAL FORMULA

Frequency, GHz	Attenuation, dB/m
16.2	2.9
20	3.0
35	3.4
44	3.5

III. TREE EXPERIMENT

To measure the effect of parking a terminal beneath a tree, an experiment was performed on the Lincoln Laboratory Antenna Test Range in which a small, densely leaved swamp maple was interposed in the transmission path to a breadboard SCOTT antenna (Fig. 1). The tree was originally about 30 feet tall, had one side trimmed away, and was supported in front of the SCOTT antenna, simulating as closely as possible the situation of the antenna looking straight up through the tree. Measurements of received signal were made at 20 and 44 GHz before and after the tree was in place. The tree was then gradually trimmed away until attenuation was reduced to 3 dB. The experiment was performed as rapidly as possible, lasting about 4 hours on 17 August 1981, so that the leaves had little chance to dry out. Figure 2 shows a jeep parked under the tree before it was felled, and Fig. 3 shows a view looking up from the jeep toward the sky. The leaves were relatively small, the largest being less than 3 inches long. Figure 4 is a tracing of some of the leaf outlines.

The breadboard SCOTT antenna, mounted on an antenna rotator at the Antenna Test Range, is shown on the right in Fig. 5. A reference dish is on the tripod on the left. The SCOTT antenna consists of a 24-inch aperture offset parabolic reflector with a dual-frequency feed. Polarization at both

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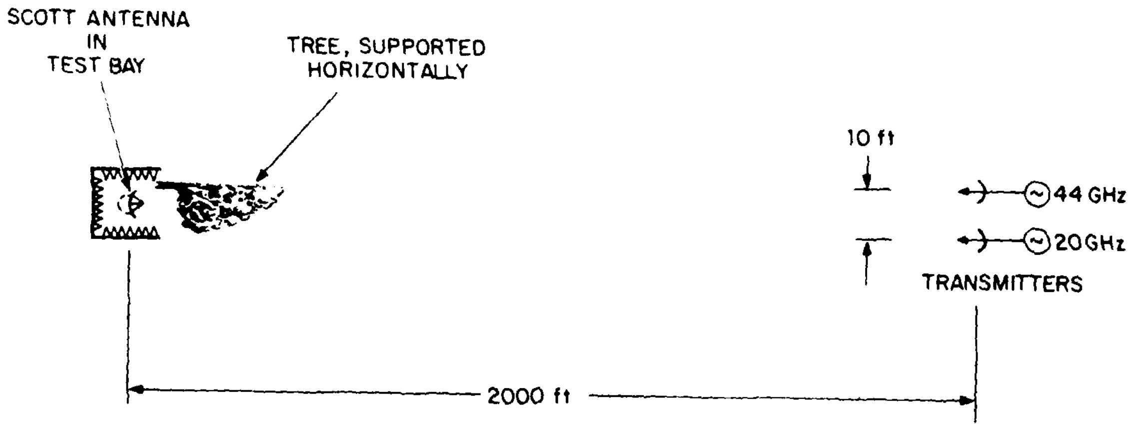

Fig. 1. Plan view of antenna test range.

Fig. 2. Jeep parked beneath maple tree before tree was cut down.

Fig. 3. View looking up from jeep.

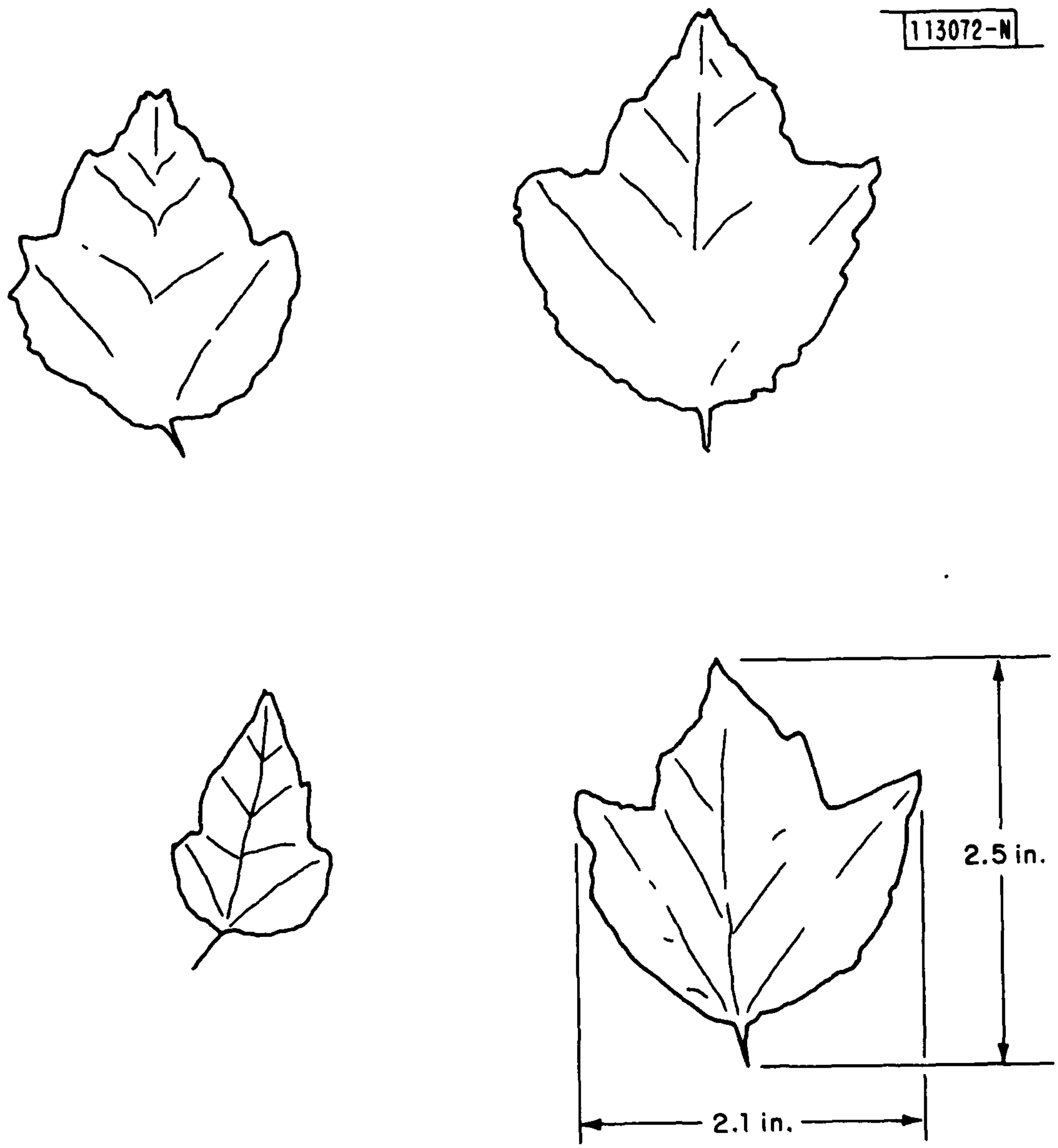

Fig. 4. Typical leaf outlines.

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Fig. 5. Breadboard SCOTT antenna facing transmitters.

frequencies was right-hand circular. Figure 6 shows the partially trimmed tree being placed in front of the antenna, and Fig. 7 shows the tree in place. The 2 x 4 supports are outside of the antenna beam and were found experimentally to have no effect on the transmission. Figure 8 shows a view from the center of the SCOTT antenna looking toward the transmitting antenna building, 2,000 feet away. No large branches were placed in the transmission path, because it was assumed any branches larger than 1/4 inch in diameter would severely attenuate the signal. The transmitting antennas were also right-hand circularly polarized.

The path through the entire tree was approximately 7 meters in length. Measured attenuation was 30 dB at 44.5 GHz and 27 dB at 20 GHz, or 4.3 and 3.9 dB/meter, respectively. These values are slightly higher than those predicted from the Georgia Tech results (Table III), which were based on horizontal, rather than vertical, propagation through treetops. Note that the measurements show only a weak frequency dependence. This indicates that the tree cannot be represented by a simple model consisting of a uniform conducting medium or of a dielectric constant and loss tangent independent of frequency, which would have an attenuation in dB/meter proportional to frequency.

After this initial measurement, the lowest layer of tree branches was trimmed away (Fig. 9), providing a view from the SCOTT antenna as shown in Fig. 10. Attenuation was thus reduced to 24 and 21.5 dB at 44.5 and 20 GHz, respectively. The tree was then trimmed further (Fig. 11), providing the view shown in Fig. 12. At this point, about half the tree had been trimmed away. Measured attenuation values were now 14 dB at 44.5 GHz and 12 dB at 20 GHz, slightly less than half the original values. The values of α in dB/meter were now approximately 4.0 at 44.5 GHz and 3.4 at 20 GHz. The tree was then trimmed so that only the topmost branches remained, as shown in Fig. 13. The transmitter building was now visible through a halo of leaves. Attenuation values were reduced to 3.5 dB at 44.5 GHz and 3.0 dB at 20 GHz. The exact amount of foliage in the beam was hard to define in this case, but it seemed to represent an average path of less than a meter.

In addition to measuring attenuation, we also recorded the main lobe of the antenna pattern. The general pattern shape was maintained, but the main lobe showed added ripples, probably caused by multipath scattering from the tree. After the last measurement was made, the tree was hosed down to simulate rain on the leaves. There was less than 1 dB change in attenuation, but the multipath effect seemed to increase slightly, as evidenced by increased ripples. Figure 14 shows antenna patterns for this last case. Finally, the tree was removed; the received signal then returned to its initial value.

Rain attenuation in dB tends to be proportional to frequency, so that a typical EHF satellite communications system would need about twice as much margin, in dB, at 44 GHz as it does at 20 GHz to equalize the probability of

Fig. 6. Positioning partially trimmed tree in front of SCOTT antenna.

Fig. 7. Tree supported in front of SCOTT antenna.

Fig. [illegible]. View facing transmitters, with majority of branches and leaves attached to tree.

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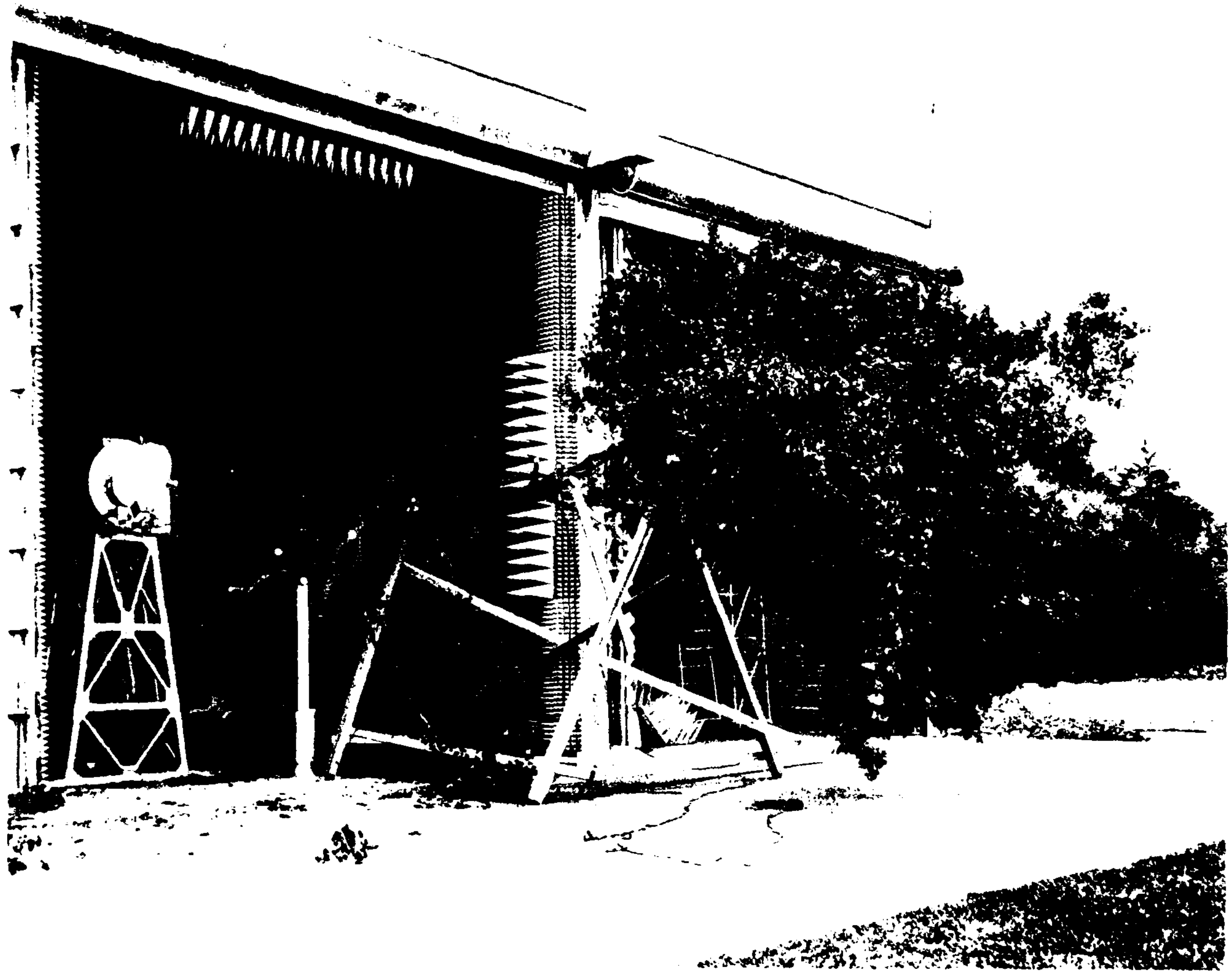

Fig. 9. View of tree with lower layer of foliage removed.

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Fig. 10. View facing transmitter when lower layer of foliage was removed.

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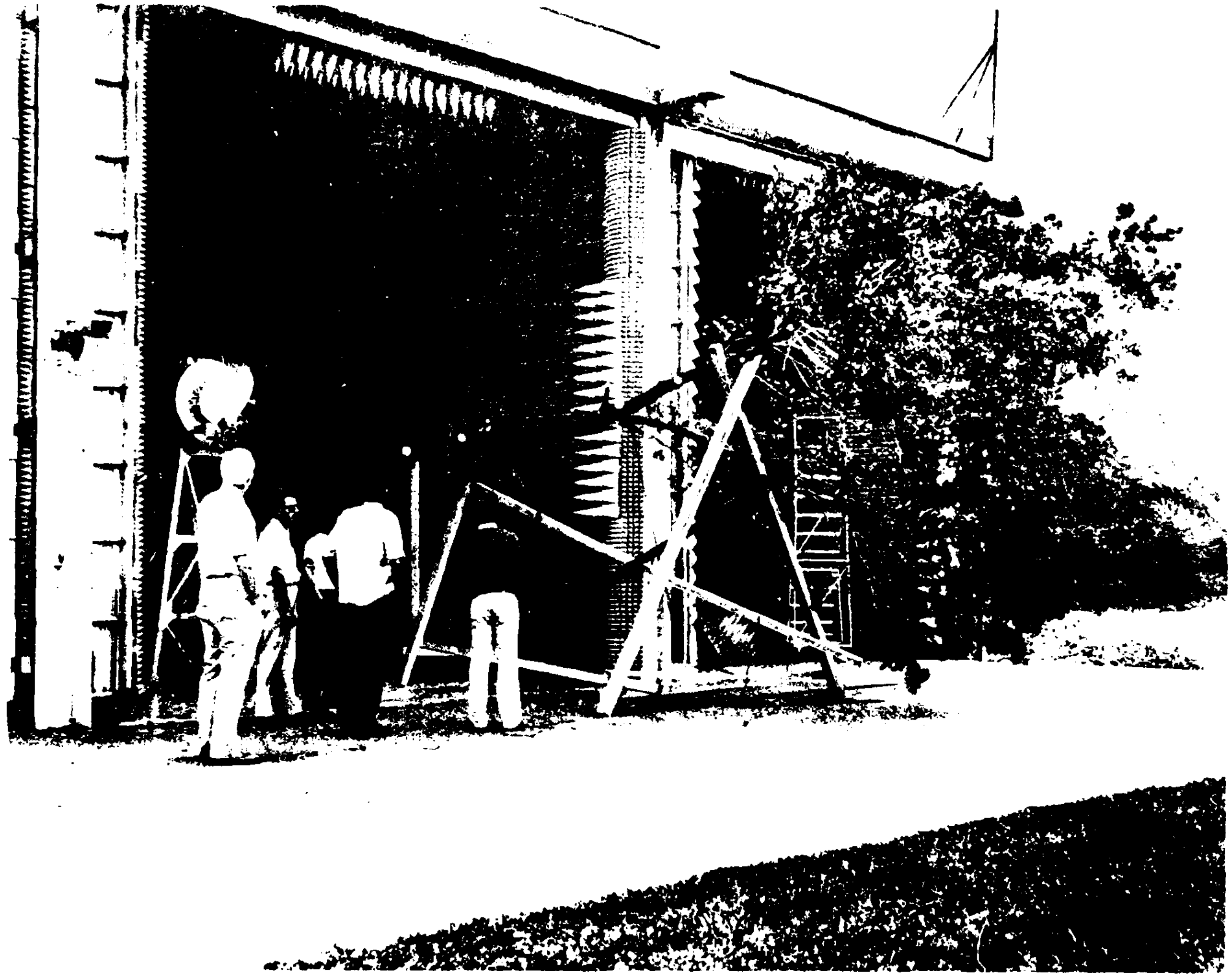

Fig. 11. View ot tree when about half trimmed.

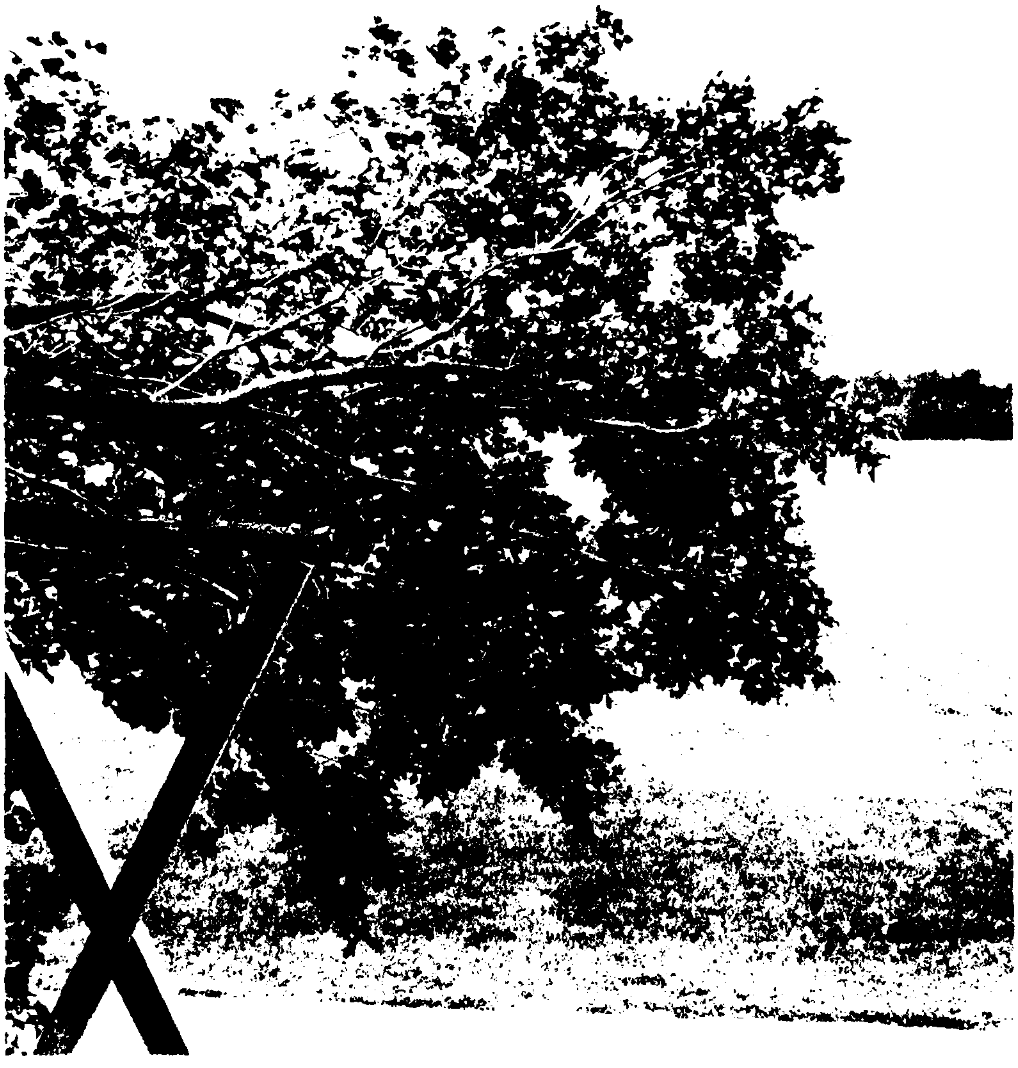

Fig. 12. View facing transmitters when tree was about half trimmed.

Fig. 13. View facing transmitters when majority of foliage was removed from tree.

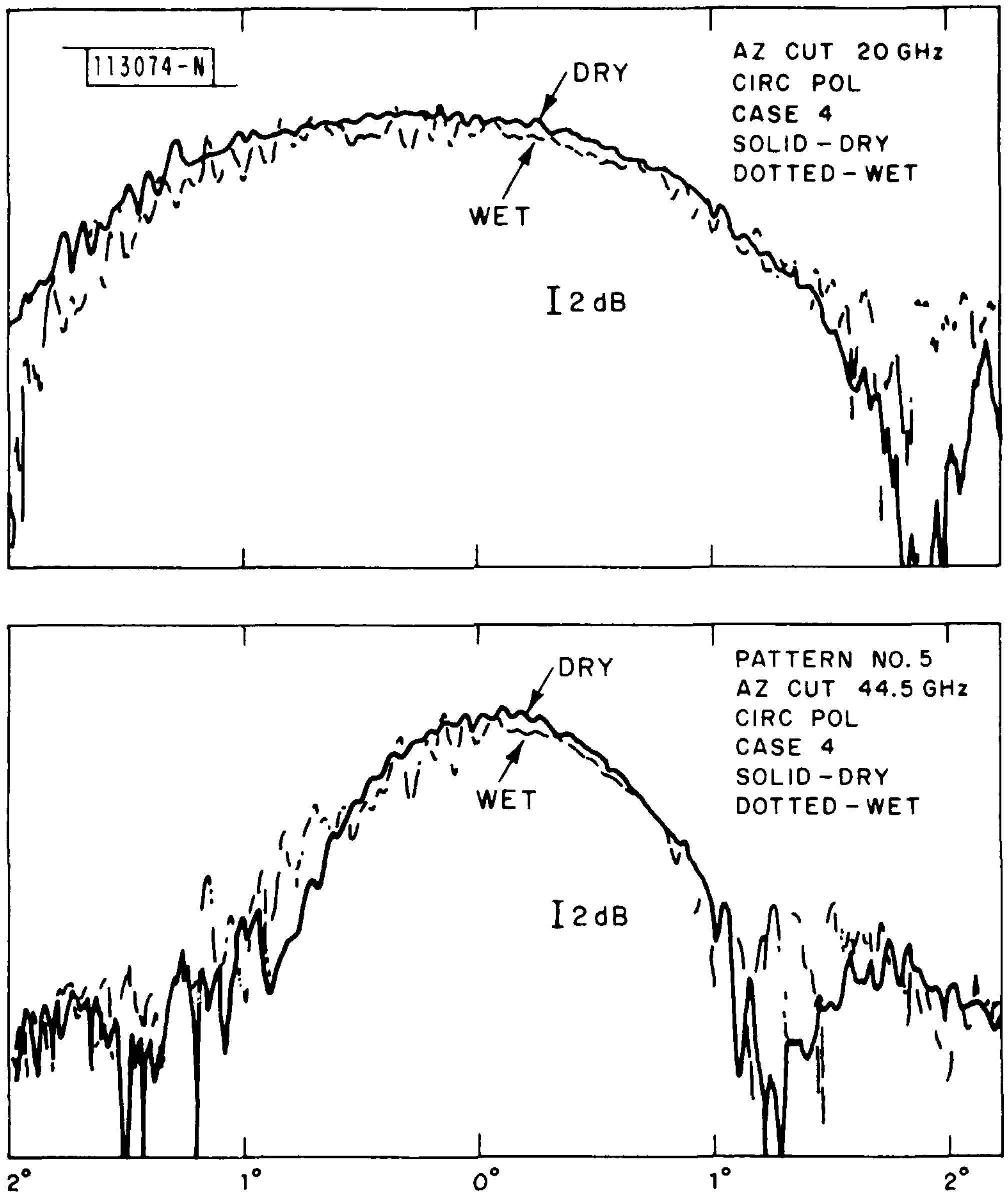

Fig. 14. Antenna patterns for wet and dry foliage at 20 and 44.5 GHz.

path availability at each frequency. If the system margin for rain is used instead for tree attenuation, it will thus be the downlink at 20 GHz with its lesser margin that first limits performance, because there is only a small difference in tree attenuation at the two frequencies. This is borne out by our measurements and by the Georgia Tech experiments. The allowable thickness, D, of foliage between vehicle antenna and satellite thus depends on link margin, M, at 20 GHz. Based on our measurements,

$$D \cong \frac{M}{4} \; .$$

IV. INDIVIDUAL LEAF MEASUREMENTS

In an attempt to quantify further the attenuation caused by foliage, individual leaves were collected from several trees in the area. The experiment consisted of setting up a small transmitting horn antenna facing a small receiving horn antenna at both 20 and 44.5 GHz. The horns were linearly polarized and separated by either 2 or 3 inches. Maximum insertion loss was recorded when a single leaf was moved into the space between the horns. The maximum attenuation of single leaves from both swamp and sugar maples was measured to be approximately 3.5 dB at either 20 or 44.5 GHz. These measurements were made within one hour of picking the leaves. Five hours after picking, the small swamp maple leaves had apparently dried sufficiently so that attenuation was reduced by 1.0 to 1.5 dB. After thorough drying in a vacuum, in which the leaf lost 50% of its initial weight, the measured attenuation was negligible, of the order of 0.1 dB, indicating that leaf moisture was the cause of rf loss.

An attempt was also made to determine if the loss was caused primarily by absorption or by reflection. A fresh swamp maple leaf was pressed against the horn aperture at 44.5 GHz and the reflected power compared with that from a flat metal plate, which has close to 100% reflection. The reflection from the leaf was 8.5 to 9 dB less than that of the metal plate, indicating that 0.6 dB of the measured 3.5 dB leaf loss was caused by reflection, the remainder due to absorption.

In addition to the measurements on a typical deciduous leaf (i.e., the maple), measurements were made on white pine needles. These needles are about 2 1/2 inches long, 0.02 inch wide, and grow in sprays of 5 needles. A single spray of 5 needles, when placed between the horns, gave the following results in Table IV.

TABLE IV

PINE NEEDLE RESULTS

	Attenuation, dB	
Freq., GHz	Parallel Polarization	Perpendicular Polarization
20	0.7 - 1.0	0.0 - 0.1
44.5	1.5	0.2

A small natural cluster of 5-needle sprays was also measured. It exhibited 7 dB attenuation for parallel polarization and 3 dB attenuation for perpendicular polarization at 44.5 GHz and 6 dB for parallel and 1 dB for perpendicular at 20 GHz. Since the needles on a tree are randomly oriented, the expected attenuation for circular polarization will be the average of those measured above. Based on these measurements, we would not expect pine trees to have less attenuation than broad-leafed trees for an equivalent path length through the tree.

V. CONCLUSIONS

Green foliage, with its high water content, is a severe attenuator of EHF waves. A single growing maple leaf can be expected to attenuate a signal at 44 or 20 GHz by about 3.5 dB. This implies that if the view of the sky from the ground terminal is completely obscured, the expected attenuation is at least 3.5 dB, possibly much more. Thus, for voice communication, it is desirable that the view of the sky be only partially obscured by leaves.

The above comments apply to deciduous trees in full leaf. Dried leaves have little attenuation. Evergreen trees can be expected to attenuate signals at least as much as deciduous trees in full leaf. In addition, no major tree limbs or trunks can be allowed to block the line of sight.

NOTE:

A study of point-to-point propagation through groves of trees at 9.6, 28.8, and 56.7 GHz has just been completed by the Institute of Telecommunication Sciences under contract to Dr. F. Schwering of the Department of the Army, Ft. Monmouth. Their final report should be available in October 1981. The experiment measured horizontal propagation at various heights and distances through the trees. Dr. Schwering, in a telephone conversation, confirmed our finding that attenuation was only weakly dependent on frequency. He thought that our suggested value of 4 dB/meter was a little higher than measured by ITS. Further comparison of ITS work with ours and others will have to wait on receipt of the ITS report.

APPENDIX A

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MODELING THE INCREASE IN LOSS CAUSED BY PROPAGATION THROUGH A GROVE OF TREES

by Mark Weissberger and Juergen Hauber
of the IIT Research Institute Staff at the
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Annapolis, Maryland 21402

The additional loss caused by the intervention of a small (< 200 meter) grove of trees between two antennas is often modeled as (Eq. 1) $L = \alpha(F) \cdot D$ where L is the added loss in dB, α is the differential attenuation in dB/m, F is the frequency in GHz, D is the depth of the grove in meters. Measurements in forests at temperate latitudes were reviewed and new insights into the applicability of this formula were gained. These include:

1. The most-cited data set (Saxton & Lane, *Wireless World*, May 1955) covers $0.1 < F < 3.2$ and $24 < D < 200$, but $F \cdot D$ is always less than 80. The data are from England and Pennsylvania.

2. LaGrone's (*Proc. IRE*, June 1960) curve fit to the Saxton data, $\alpha = 0.25\ F^{0.77}$ (Eq. 2), also satisfies the $F \cdot D < 80$ portion of a data set taken by McQuate (*ERL 65-ITS 58-1*, ITS, March 1968) in Colorado. The equation predicts too much loss for larger values of $F \cdot D$, however.

3. $\alpha = 1.33\ F^{0.284}\ D^{-0.412}$ (Eq. 3) describes the entire McQuate data set ($3 < F \cdot D < 840$) as well as the entire Saxton data set. The McQuate data encompassed $15 < D < 90$ and $0.2 < F < 9.2$.

4. The California measurements of Frankel (SRI, *Packet Radio Note 254*, May 1978) are more accurately described by an equation of the form of Eq. 3 than they are by an equation of the form of Eq. 2. In this case, $F = 1.8$, $50 < D < 150$, $90 < F \cdot D < 280$.

5. The data in these three sets involved blockage by branches with leaves. Propagation through clusters of bare tree trunks causes, on the average, less loss.

6. The decrease of α with D in Eq. 3 is not predicted by the theory of propagation through an infinite medium -- whether it is filled with discrete scatterers or a lossy-dielectric continuum. A reasonable physical explanation of the diminishing α is that it represents an increasing percentage of the energy being propagated outside the branchy region -- either in free space or a region occupied by bare trunks.

ACKNOWLEDGEMENTS

The tree experiment was planned and managed by Robert Burns, with the assistance of Jeffrey Perry and Erik Fredrikson. Donald Brown made the measurements on individual leaves. Assistance in determining the water content of the leaves was provided by Edward Murphy.

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An EHF experiment was performed in which a 30-foot maple tree was placed between a 2-foot parabolic antenna and a distant transmitting site operating at 20 and 44 GHz. The objective was to measure attenuation through foliage. Results indicate that attenuation is nearly the same at the two frequencies. A value of 4 dB/meter can be used as a rough guide for deciduous trees in full leaf.

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